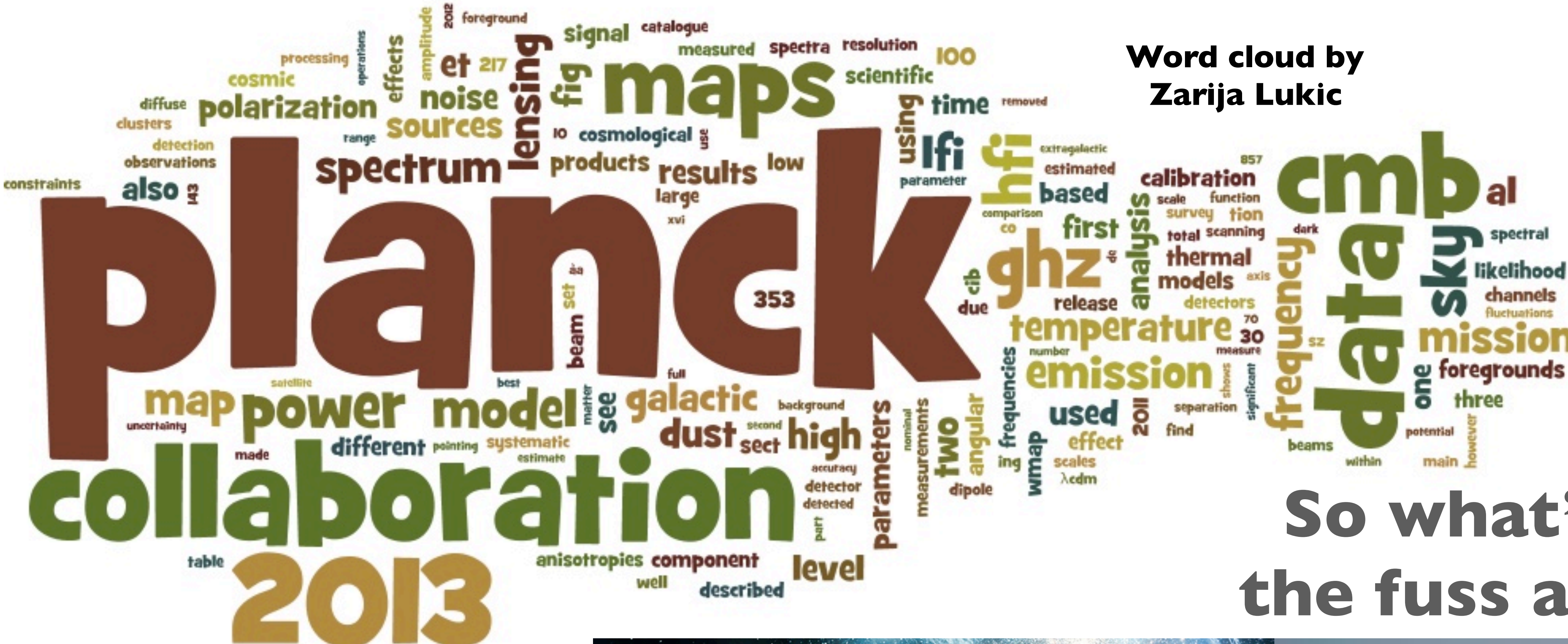
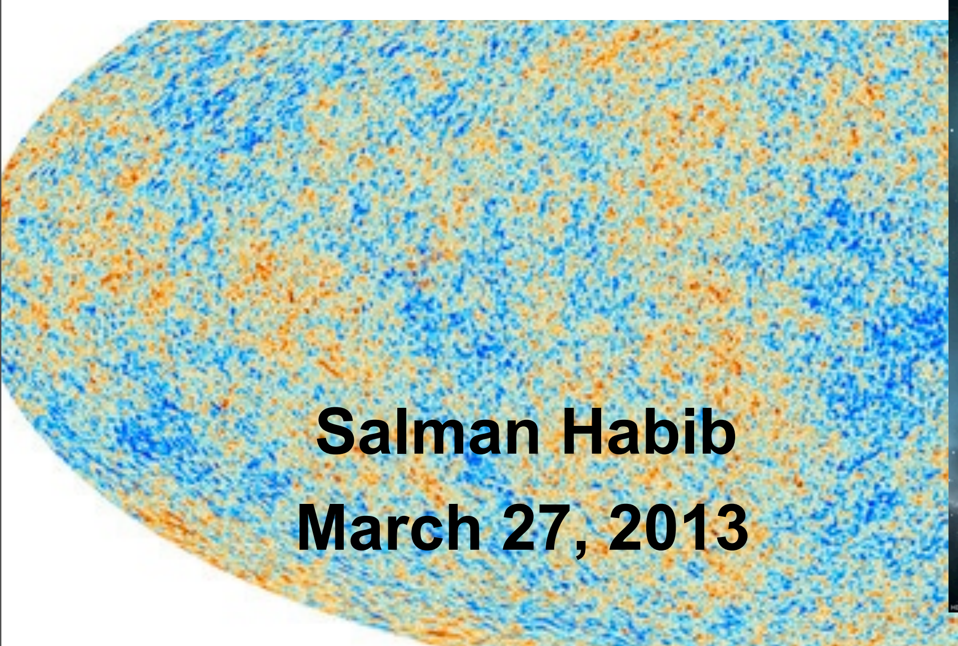
Planck: It's Finally Here



Word cloud by
Zarija Lukic

So what's all
the fuss about?

Triumph of Cosmic Metrology



Salman Habib
March 27, 2013

Modern Cosmology: A CMB-Biased Informal History

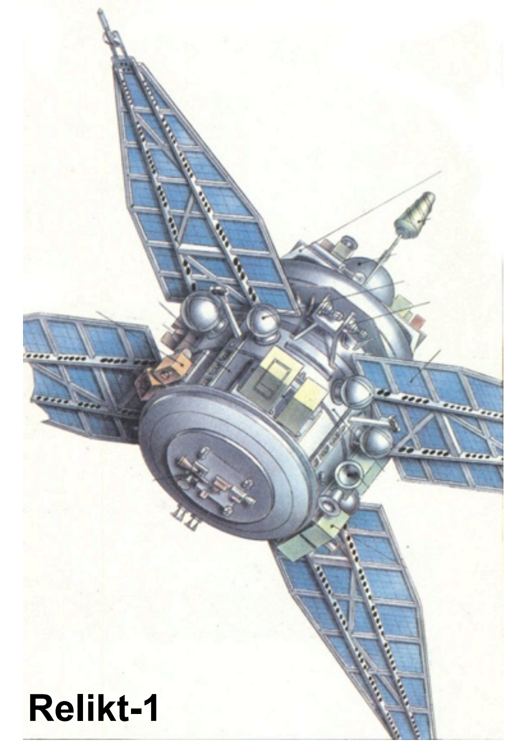
Einstein (space is dynamic, but had to be convinced)
Friedmann (cosmological solutions of GR, FRW spaces)
Lemaitre (expanding Universe, ‘Big Bang’)
Slipher/Hubble (Hubble’s law)
Zwicky (Dark Matter)
Gamow/Alpher/Hermann (nucleosynthesis, CMB)
Hoyle (Steady State)
Lifshitz/Harrison (Perturbations)
Penzias/Wilson/Dicke (CMB observed)
Misner (Horizon problem, transport processes)
Peebles/Zel’dovich (‘Physical cosmology’)
Zel’dovich (Modern cosmological constant)
Guth (Inflation)
Starobinsky/Hawking/Steinhardt/Grishchuk/Lukash/Novikov (Perturbations from inflation)
Bardeen/Mukhanov/Unruh (Perturbations II)
Huchra/Geller (CfA survey)
COBE/COBRA/Relikt-1 (CMB temperature, temperature anisotropy)
Jungman/Kamionkowski/Knox/Kosowsky/Spergel (1% cosmology with CMB maps)
APM/LCRS/2dF/SDSS (Wide area imaging and redshift surveys)
Perlmutter/Reiss/Schmidt (Accelerating Universe)
Boomerang/Maxima/WMAP (Initial CMB acoustic peaks)
DASI (CMB polarization E-mode)
ACT/SPT (High-l CMB)
Planck (All sky, high-l, 9 frequencies, the ultimate temperature anisotropy measurement)

Bob Dicke

Yakov Zel’dovich

David Wilkinson

Jim Peebles

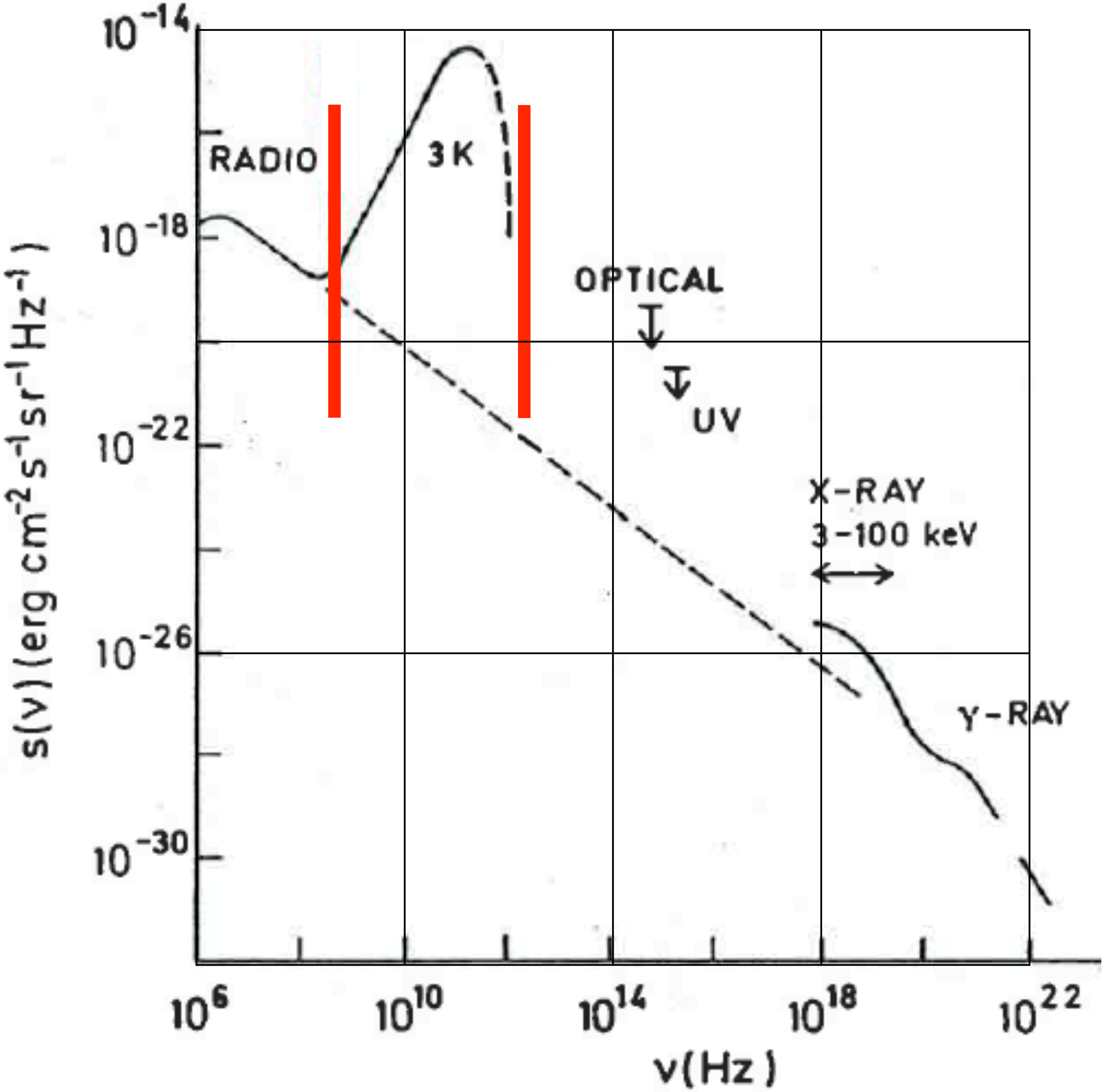


Relikt-1

Jim Gunn

Andrew Lange
1957-2010

CMB Dominance: It's Really, Really There!

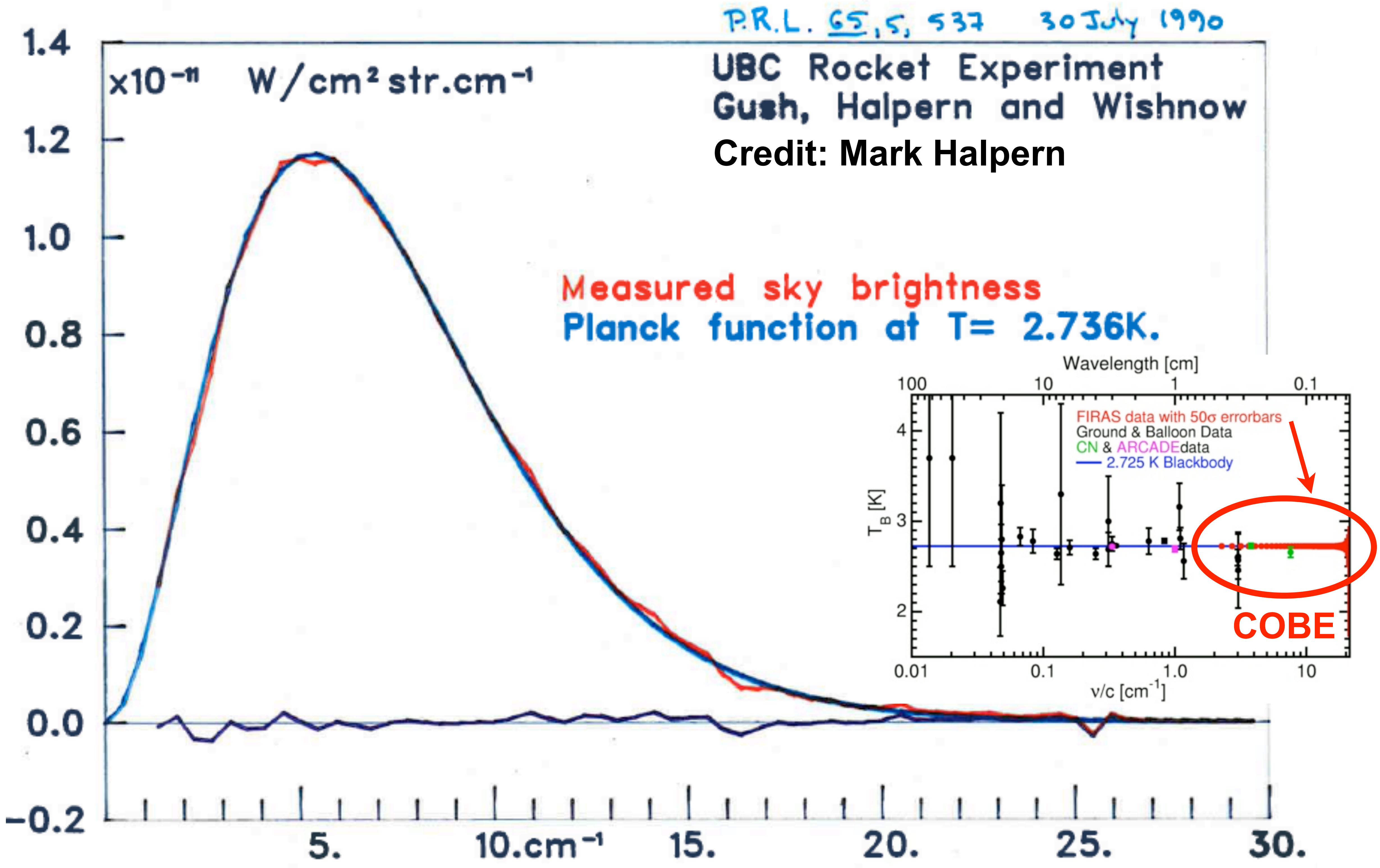


Spectrum of extra-galactic background radiation; the CMB completely dominates the sky in its 'home' waveband

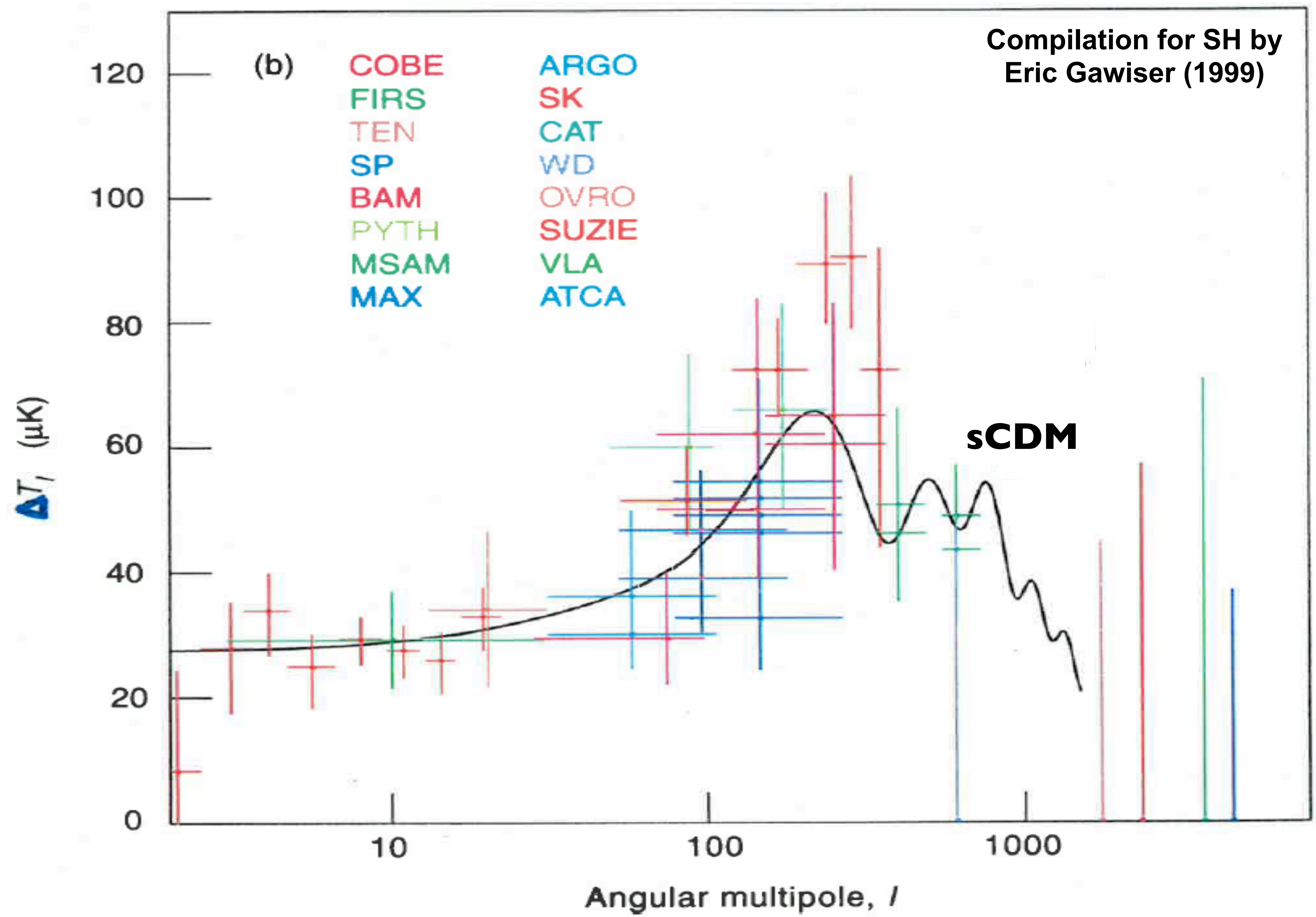
Dicke could have observed it in the 1940's when he was doing his K-band radar measurements, if he had used a cold load

Mckellar saw it in 1940 in stellar spectra (rotationally excited CN line), the implied brightness temperature is 2.729 +/- 0.027 K at 2.64 mm, but the data were not understood at that time --

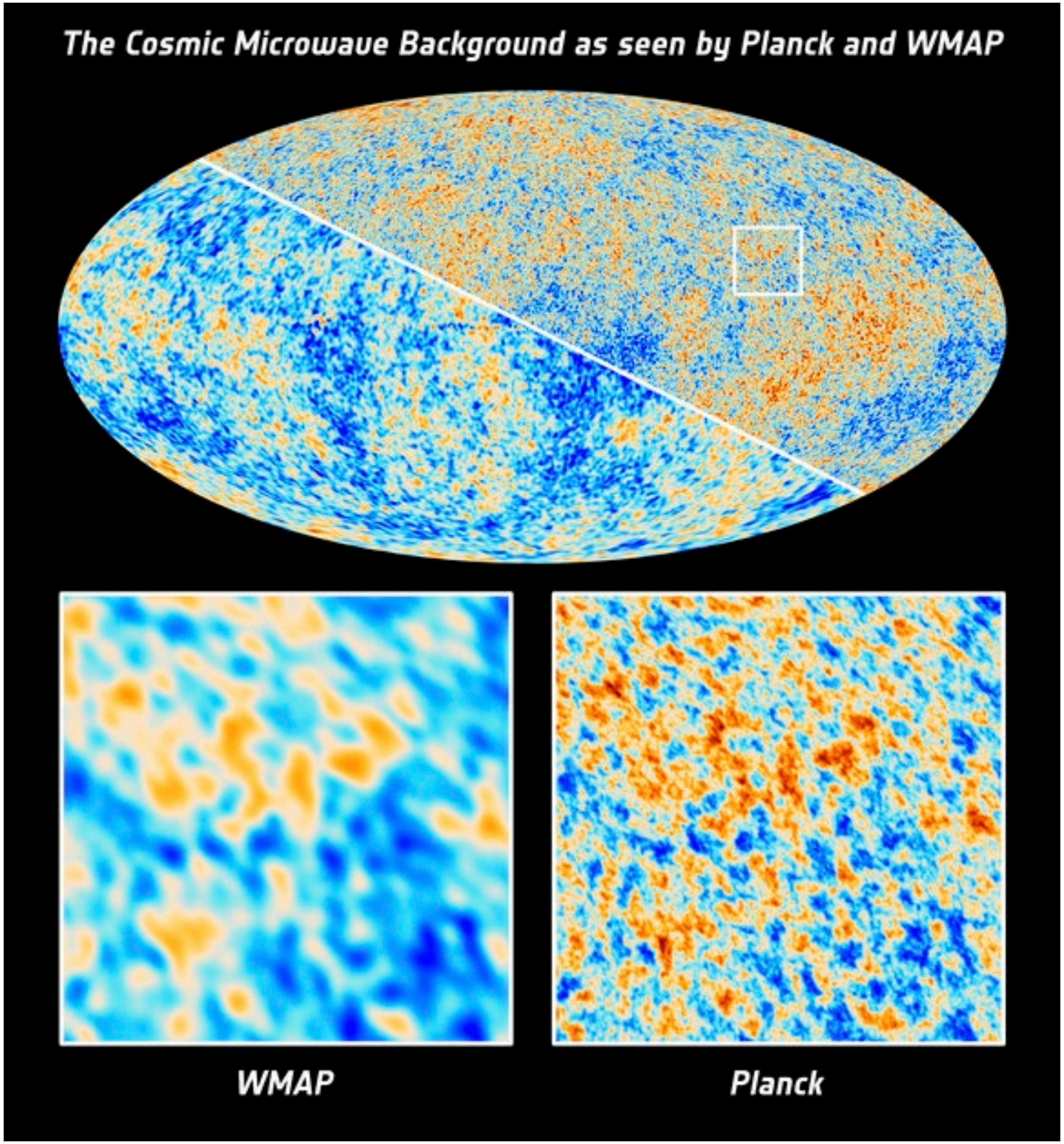
COBRA Results: An Early Modern Measurement



Temperature Anisotropy: CMB Confusion (1999)



And Here's Planck (2013) --



ESA space mission, accepted in 1996 (COBRAS/SAMBA concept). Substantially higher resolution than WMAP --

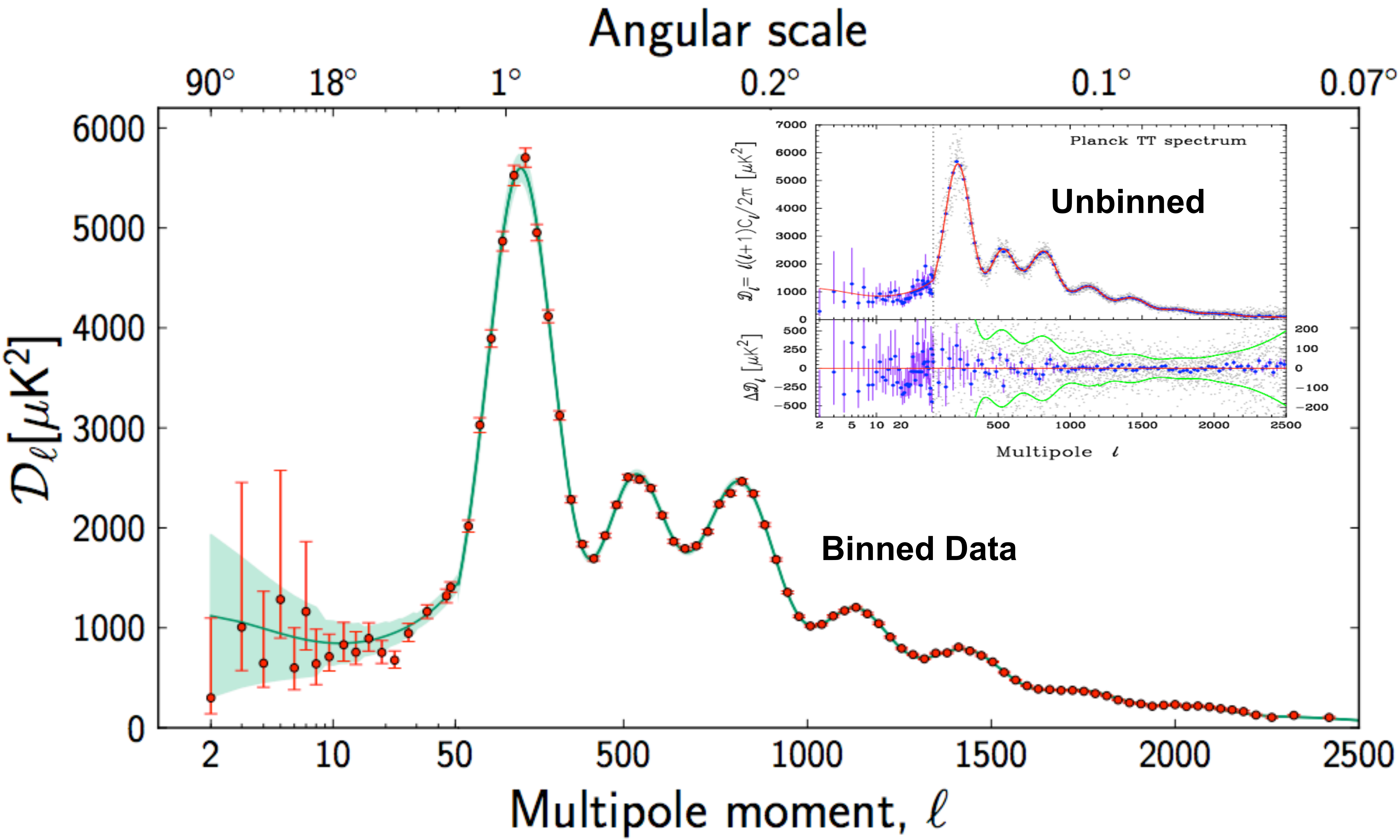
Important US contribution led by Charles Lawrence (JPL).

DOE HEP played a significant role in Planck data analysis. This work was conducted at LBNL and led by Julian Borrill.

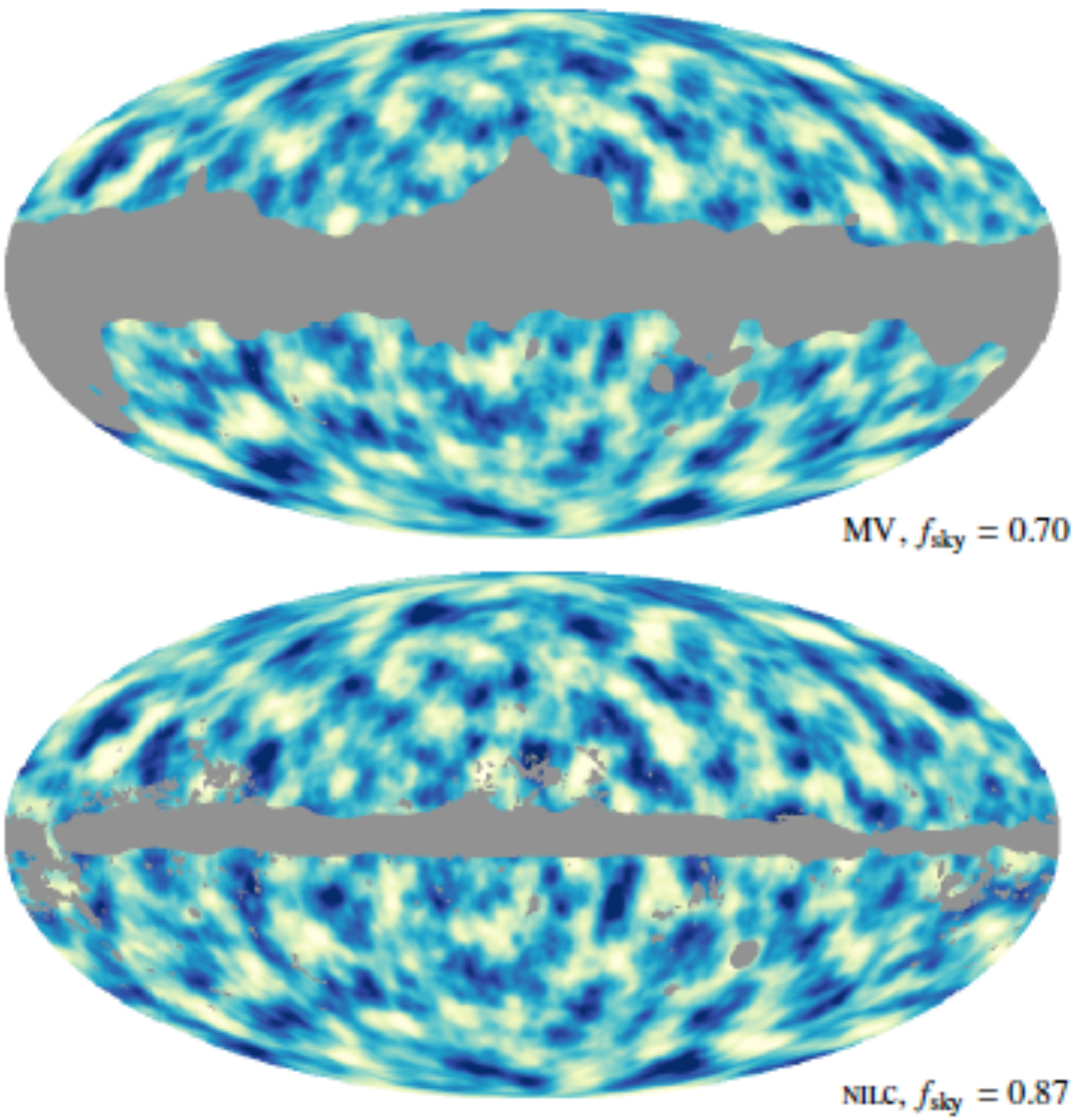
"These maps are proving to be a goldmine containing stunning confirmations and new puzzles. This data will form the cornerstone of our cosmological model for decades to come and spur new directions in research."
-- Martin White (Planck scientist, UC Berkeley/LBNL)

And Here's Planck (2013) -- Compare to 1999!

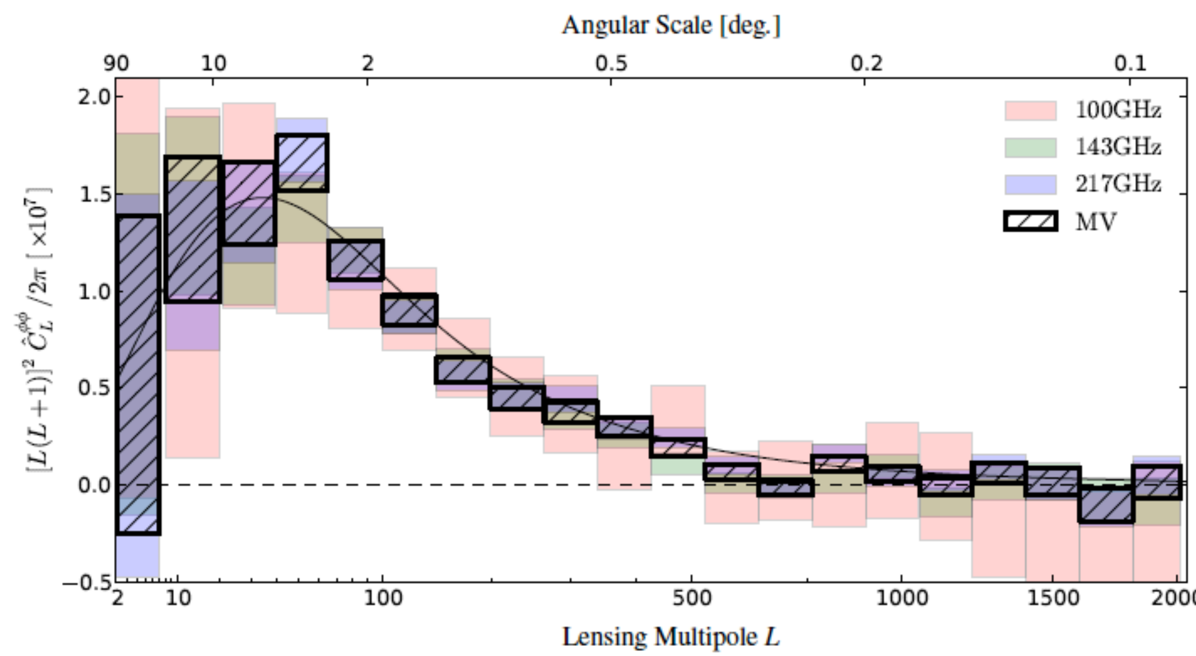
Note: Similar data from WMAP + ACT + SPT



Planck: Gravitational Lensing of the CMB



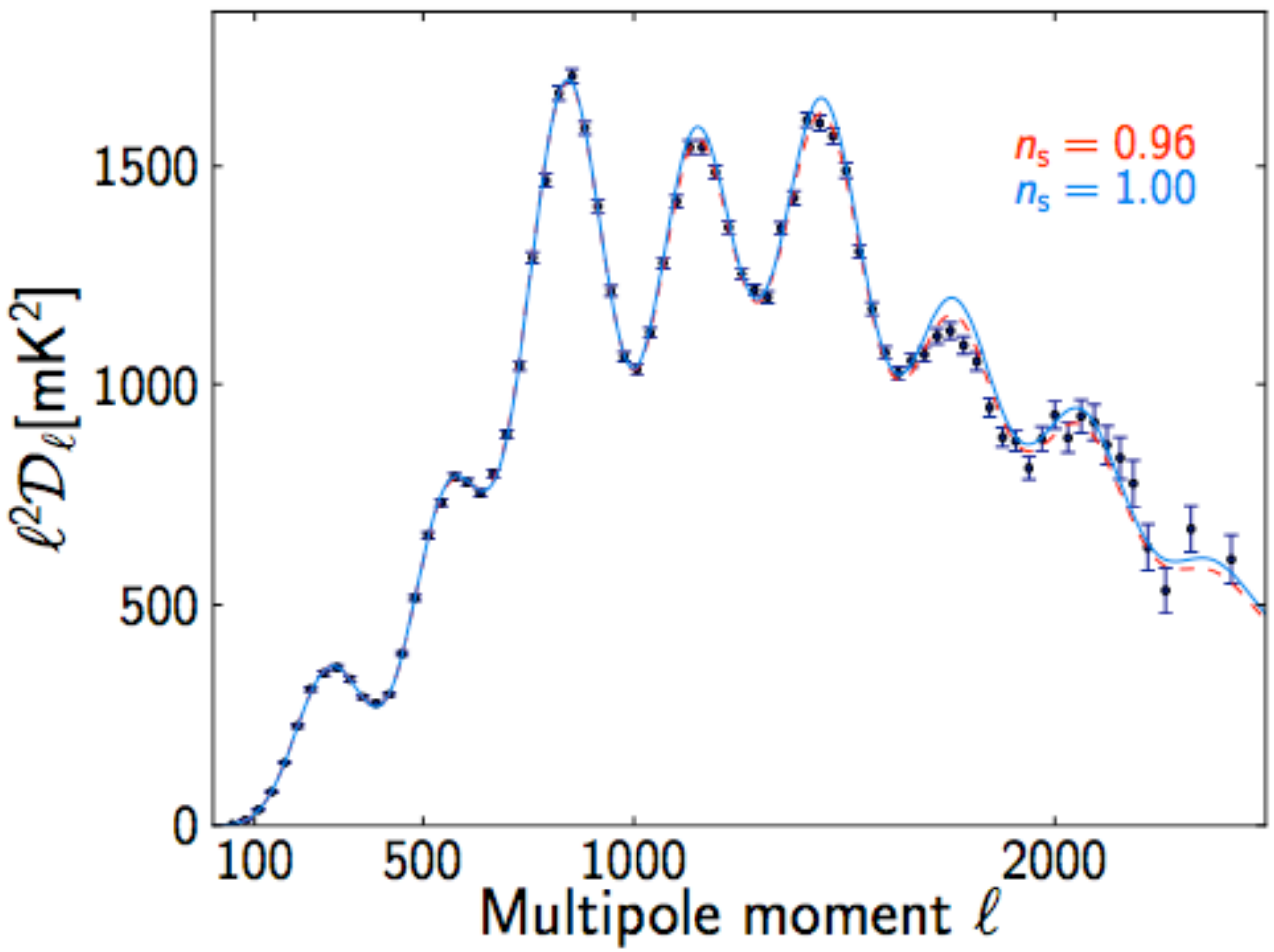
Wiener-filtered potential maps (Galactic coordinates, Mollweide projection); two different reconstructions

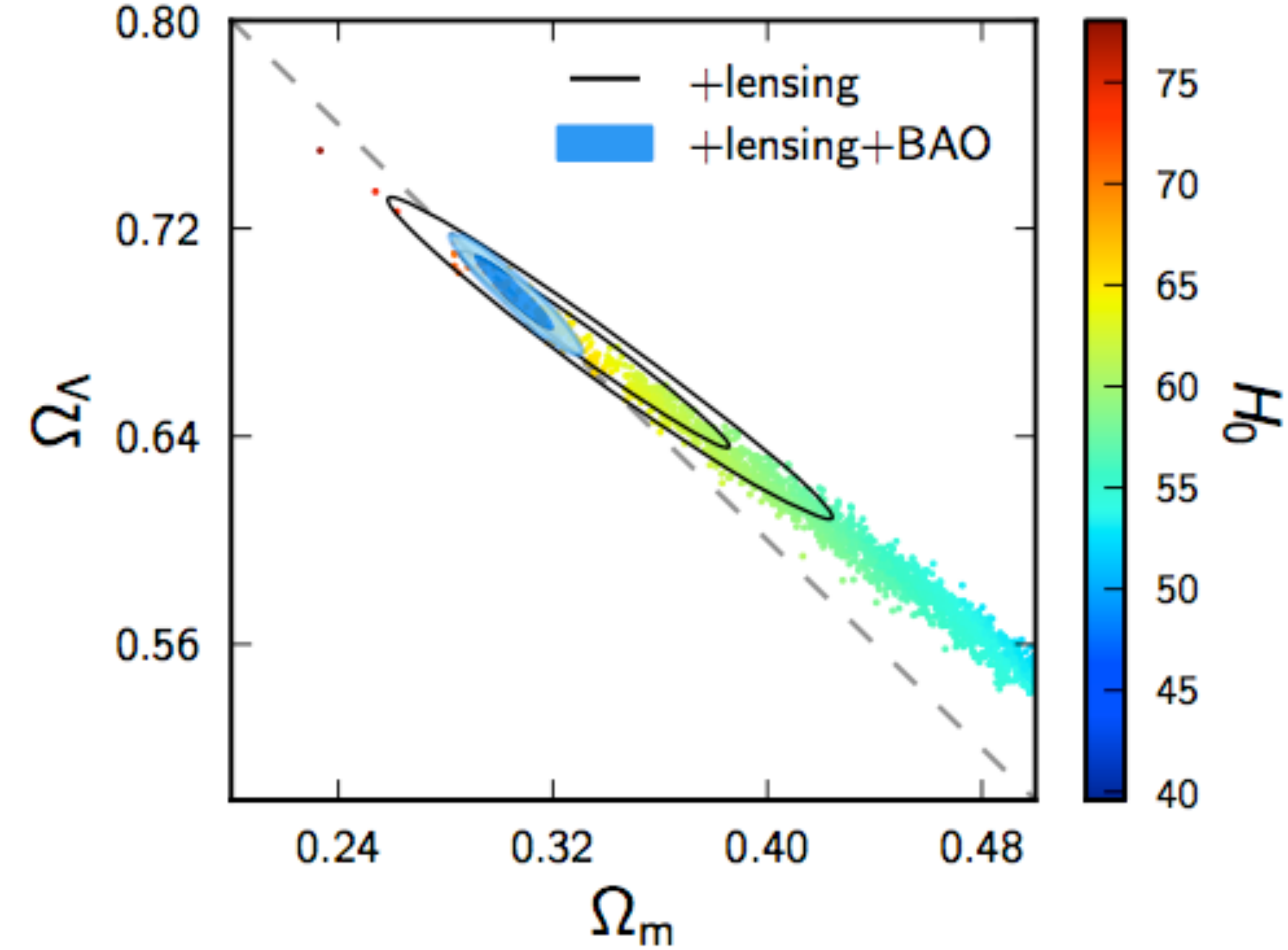


Planck lensing potential power spectrum at three frequencies, the black line is the best-fit LCDM model

Planck measures the lensing of the CMB by intervening matter, detecting the effect at greater than 25 sigma. This corresponds to a 2% measurement of the rms amplitude of matter fluctuations at redshift, z~2

Inflation -- The Spectral Index and Flatness





Simple, single-field slow-roll inflation models predict the primordial spectral index, n_s<1, generically -- often considered a (mildly) smoking gun for these models. Planck rules out n_s=1 (the Harrison-Zel'dovich spectrum) at >5 sigma. Running is very small (expected), and the constraint on the scalar to tensor ratio is, r <0.1-0.3 (depending on what assumptions one makes).

Inflation predicts very small spatial curvature (of order 10 ppm). Planck lensing reconstruction helps break the CMB geometric degeneracy; combining with BAO results from redshift surveys yields stronger constraints on the spatial curvature: The spatial curvature is consistent with zero to better than a percent.

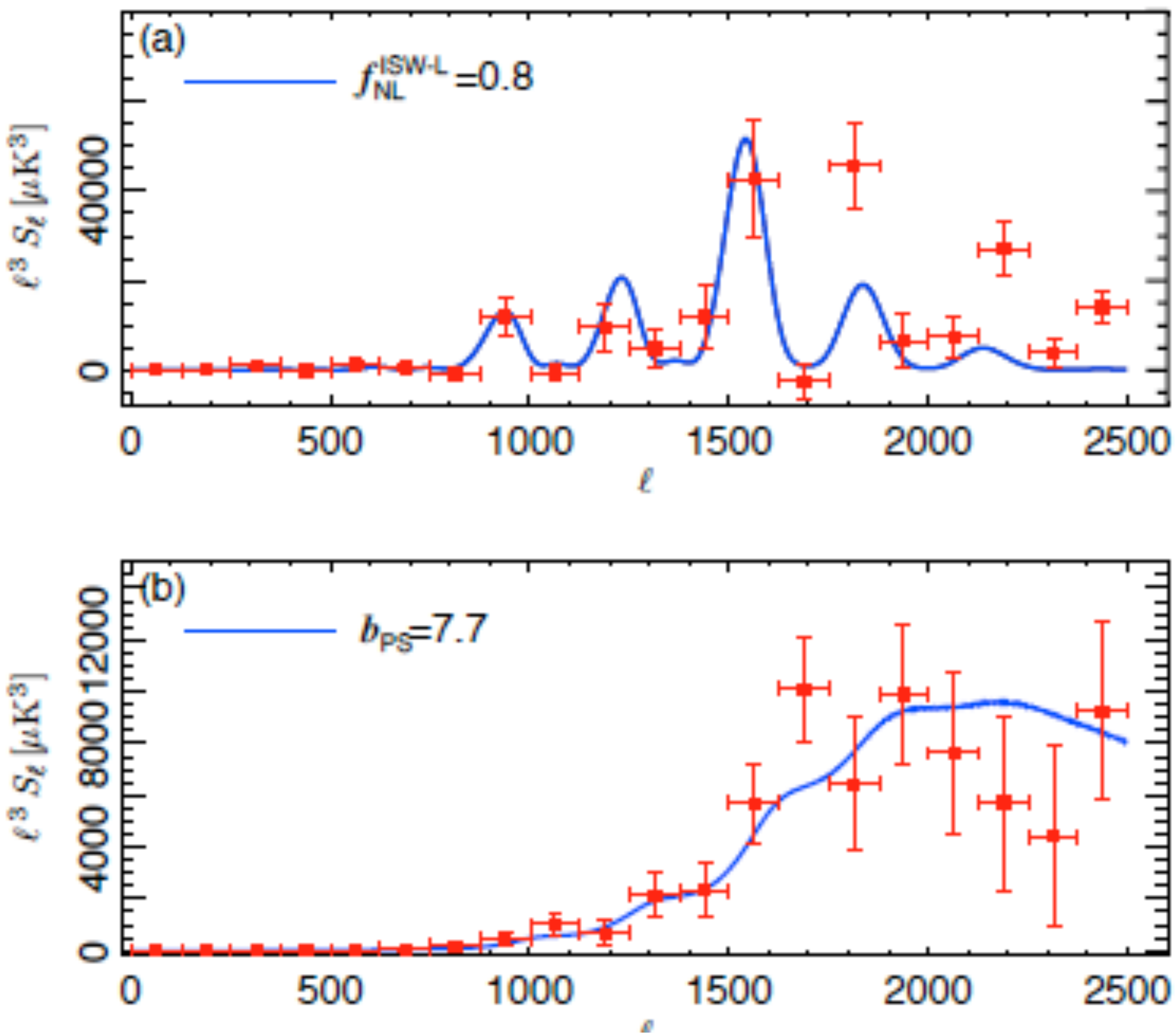
Detection of No Non-Gaussianity ;-)

Simple, single-field slow-roll inflation models predict Gaussian initial conditions. (Non-Gaussian terms are very small.) However many exotic inflation models have been built by theorists for one reason or another that predict a non-Gaussian signal. Plus alternatives to inflation (ekpyrotic models) predict measurable non-Guassianity.

So a detection of a primordial non-Gaussianity would rule out simple slow-roll inflation models, and may support alternative inflation models (yuck!) or even alternatives to inflation (bleah!).

The 'good' news -- forget about it!

The expected ISW-lensing bispectrum is seen, and diffuse point sources, but that's basically it. To quote the Planck paper, *"With these results the paradigm of standard single-field slow-roll inflation has survived its most stringent tests to date."*



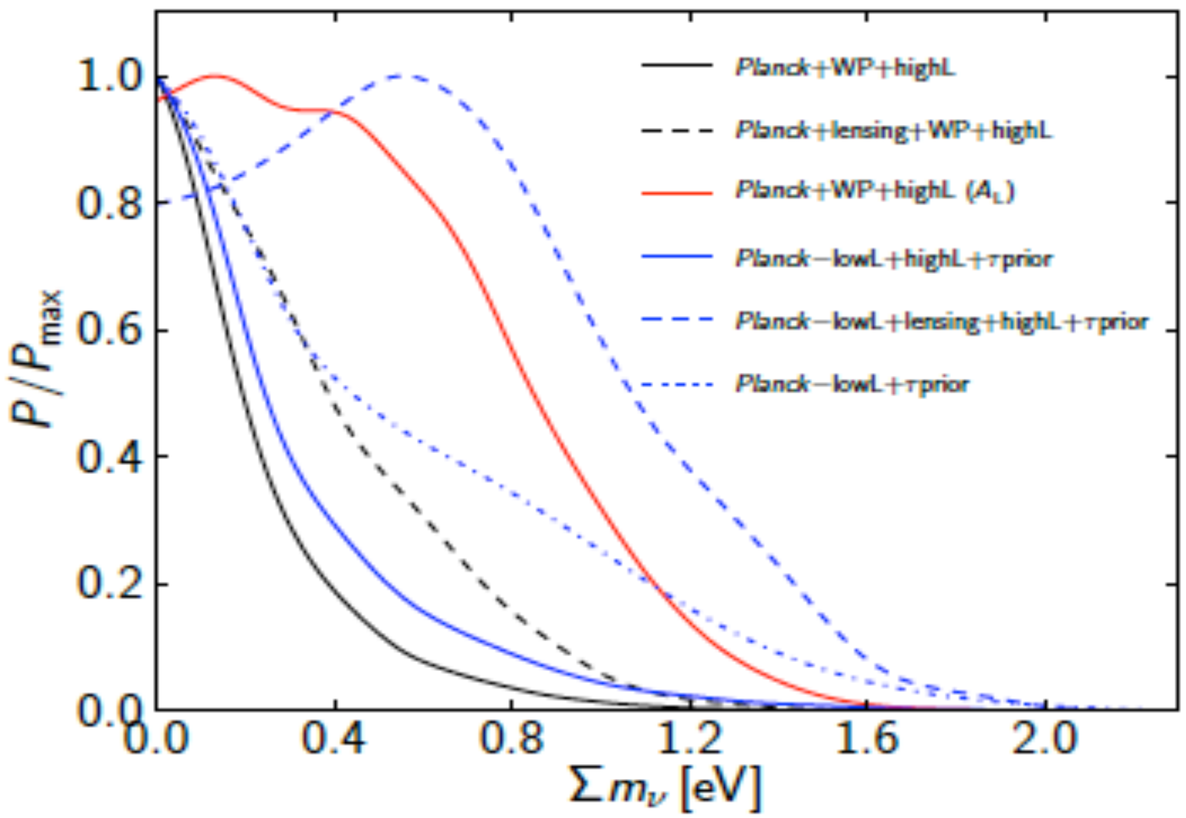
(a) Measured skew-C_l spectrum for optimal detection of the ISW-lensing bispectrum; (b) signal from Poisson point sources

Neutrinos

The CMB provides constraints on the sum of neutrino masses, this constraint is coming closer to the ~0.1 eV level expected from oscillation scenarios.

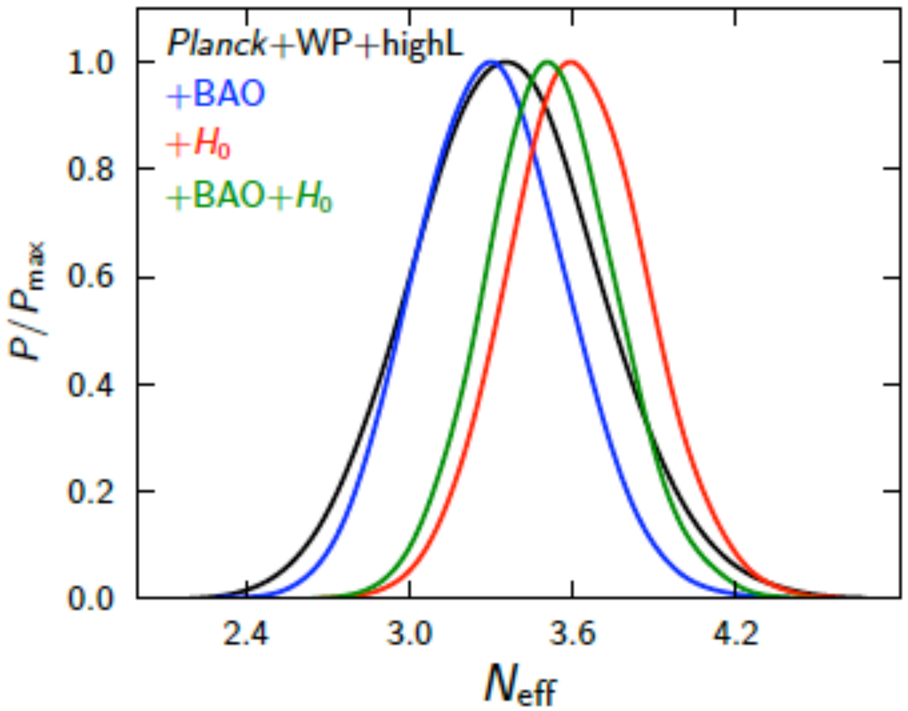
Planck's CMB data-only constraints set the sum of neutrino masses to be less than 0.66-0.85 eV (depending on the choice of CMB data used). BAO results help to break the geometric degeneracy in the angular-diameter distance to last scattering (which is sensitive to the neutrino mass), and henece help to improve the limit. Including these results, one finds the 95% upper limit to be 0.23 eV (assuming spatial flatness).

The effective number of neutrino species, N_eff, is measured by Planck (plus other CMB data) to be 3.36 +/- 0.7, adding BAO pulls it down to 3.30 +/- 0.5, adding H_0 moves it up to 3.62 +/- 0.5. The Planck team appears to gve most weight to the N_eff~3.3 result, but presumably there will be more investigation of this. In any case, Planck argues for no compelling evidence against the canonical N_eff=3.046.

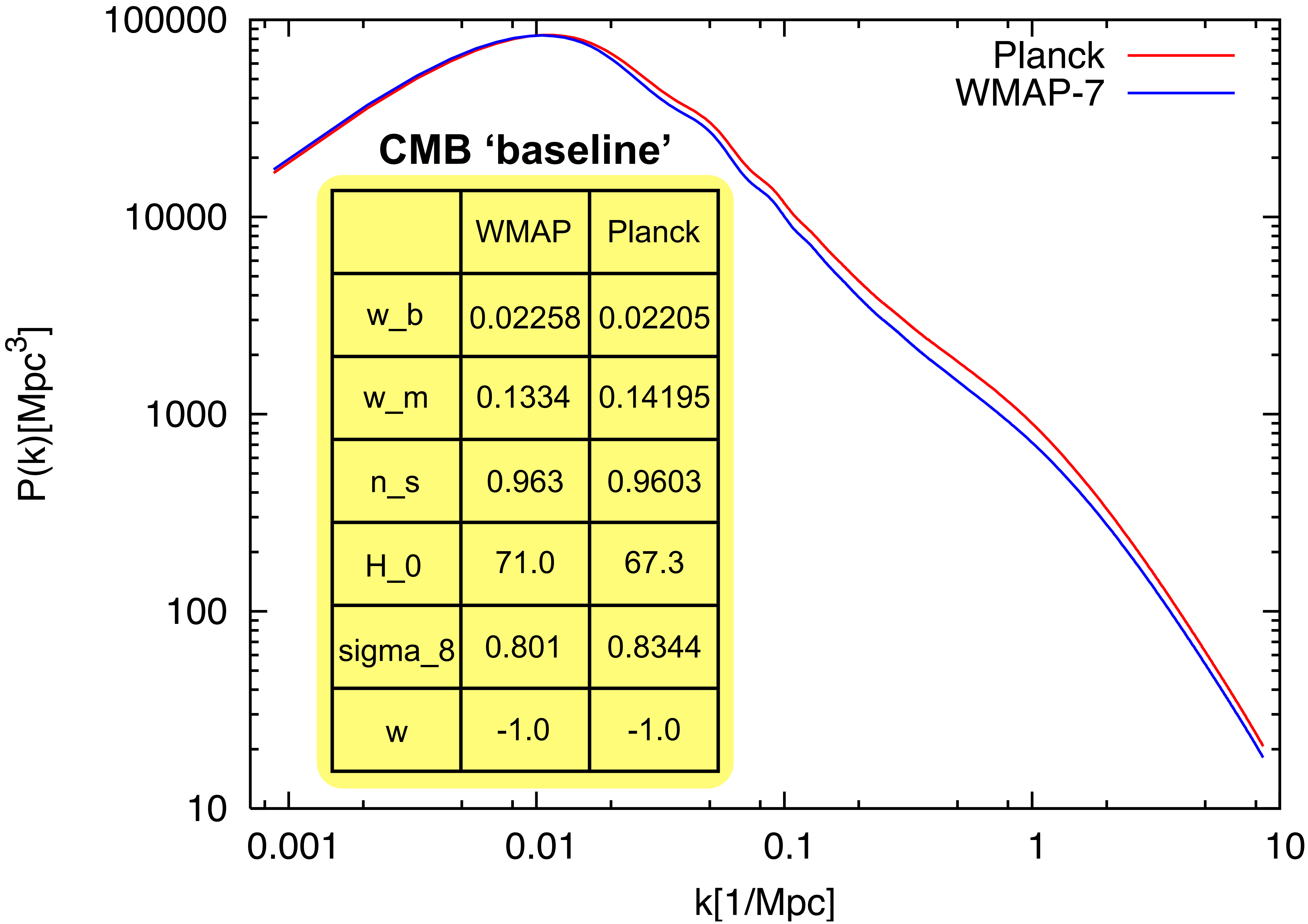


CMB data-only constraints on the sum of neutrino masses. Adding in the lensing likelihood weakens the limit on the mass sum; why this is so is not currently understood.

Marginalized posterior distribution of N_eff for different data inclusion choices



Planck Implications for Structure Formation



CMB ‘baseline’

	WMAP	Planck
w_b	0.02258	0.02205
w_m	0.1334	0.14195
n_s	0.963	0.9603
H_0	71.0	67.3
sigma_8	0.801	0.8344
w	-1.0	-1.0

Argonne/Los Alamos precision nonlinear emulator prediction for Planck parameters (Heitmann et al. 2013), in preparation

Nonlinear matter fluctuation power spectrum as predicted using Planck best-fit parameters and compared to WMAP-7

Note significantly higher power in P(k) as predicted by the Planck results; should be seen by structure formation probes (although degeneracies with bias may be an issue)

Tension with clusters may mean something (or not) --

Summary: Cosmology and Physics

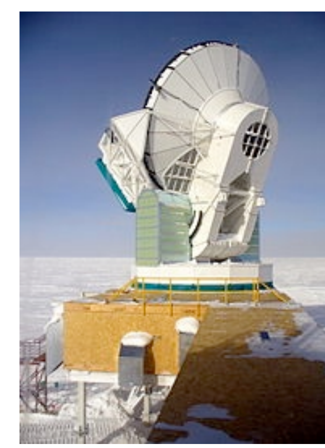
Ω_m	Actual value not too interesting, primarily useful as evidence for dark matter (although may enter some collider dark matter search analyses)
Ω_b	Actual value not too interesting, but important for consistency with BBN
Ω_K	Spatial flatness, inflation 'prior', hence important -- 0 at <1 percent level
n_s	0.959 +/- 0.007, unity ruled out at >5 sigma (simple inflation models are fine), no real evidence for running of the spectral index
w	Dark energy EOS parameter clearly important, but w=-1 is fine
σ_8	Overall normalization, not particularly interesting
$\sum m_\nu$	Upper limit ~0.2-0.3 eV including other experiments, e.g., BAO
N_{eff}	3.30 +/- 0.5, no real evidence for extra relativistic degrees of freedom
f_{NL}	Smoking gun for nonstandard inflation models, but consistent with nondetection, 2.7 +/- 5.8 (slow roll/single field modes are fine)

Suggested Planck Papers

Paper XV CMB power spectra and likelihood
Paper XVI Cosmological parameters
Paper XVII Gravitational lensing by LSS
Paper XX Cosmology from SZ cluster counts
Paper XXII Constraints on inflation
Paper XXIV Constraints on primordial non-Gaussianity

They are extremely well-written and the analyses are motivated and explained clearly

Suggested Historical Reading:



Finding the Big Bang

Jim Peebles, Lyman Page, and Bruce Partridge
Cambridge University Press, 2009